OSE OPTIMISATION IN SPACE ENGINEERING

Parameter Analysis of a Concurrent Engineering Satellite Study

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  - Concurrent Engineering at DLR
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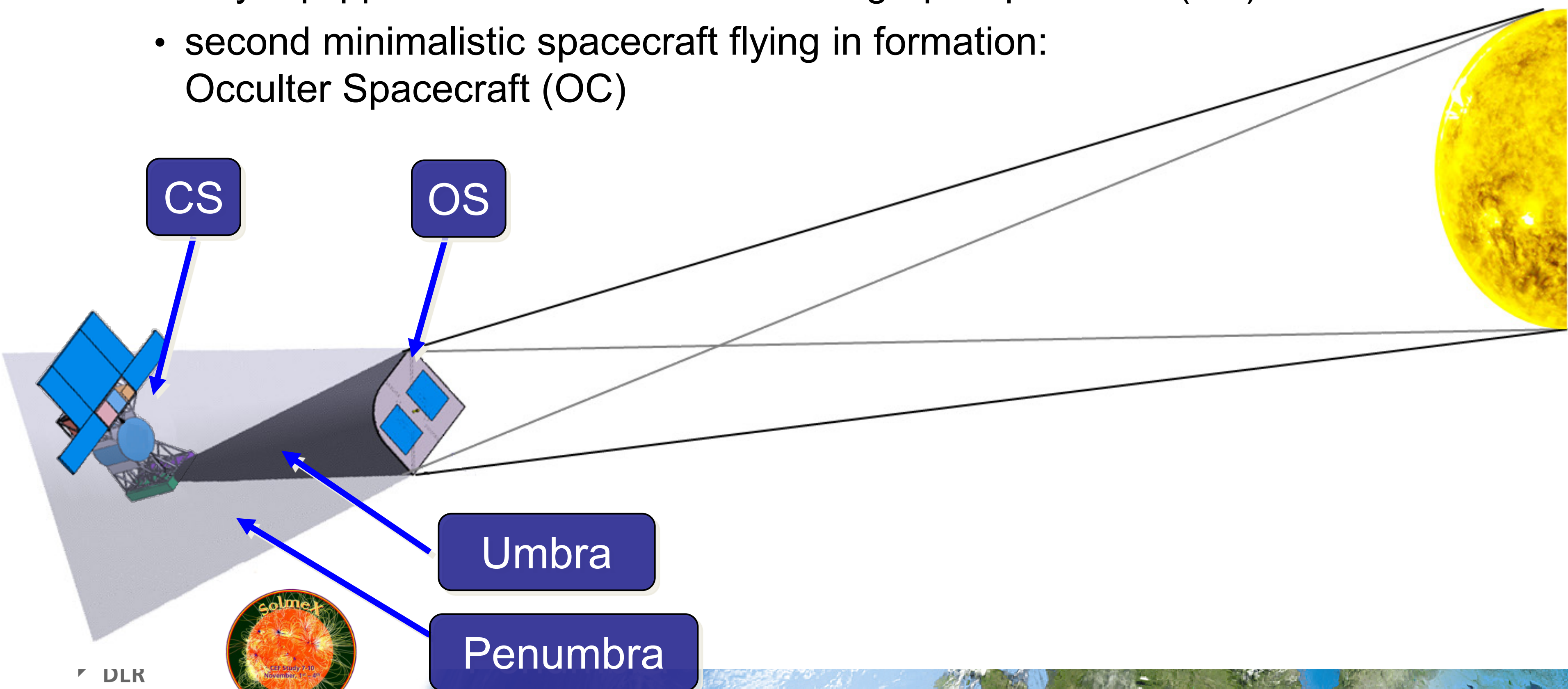
  - Meaning for MDO

SolmeX CE Study
What is SolmeX?

- Solar Magnetism Explorer proposal under lead of the Max Planck Institute for Solar System Research, answering 2010 Cosmic Vision call for M-class mission opportunity in ESA's Science Programme:
    - fully equipped science satellite: Coronagraph Spacecraft (CS)
    - second minimalistic spacecraft flying in formation: Occulter Spacecraft (OC)



SolmeX CE Study

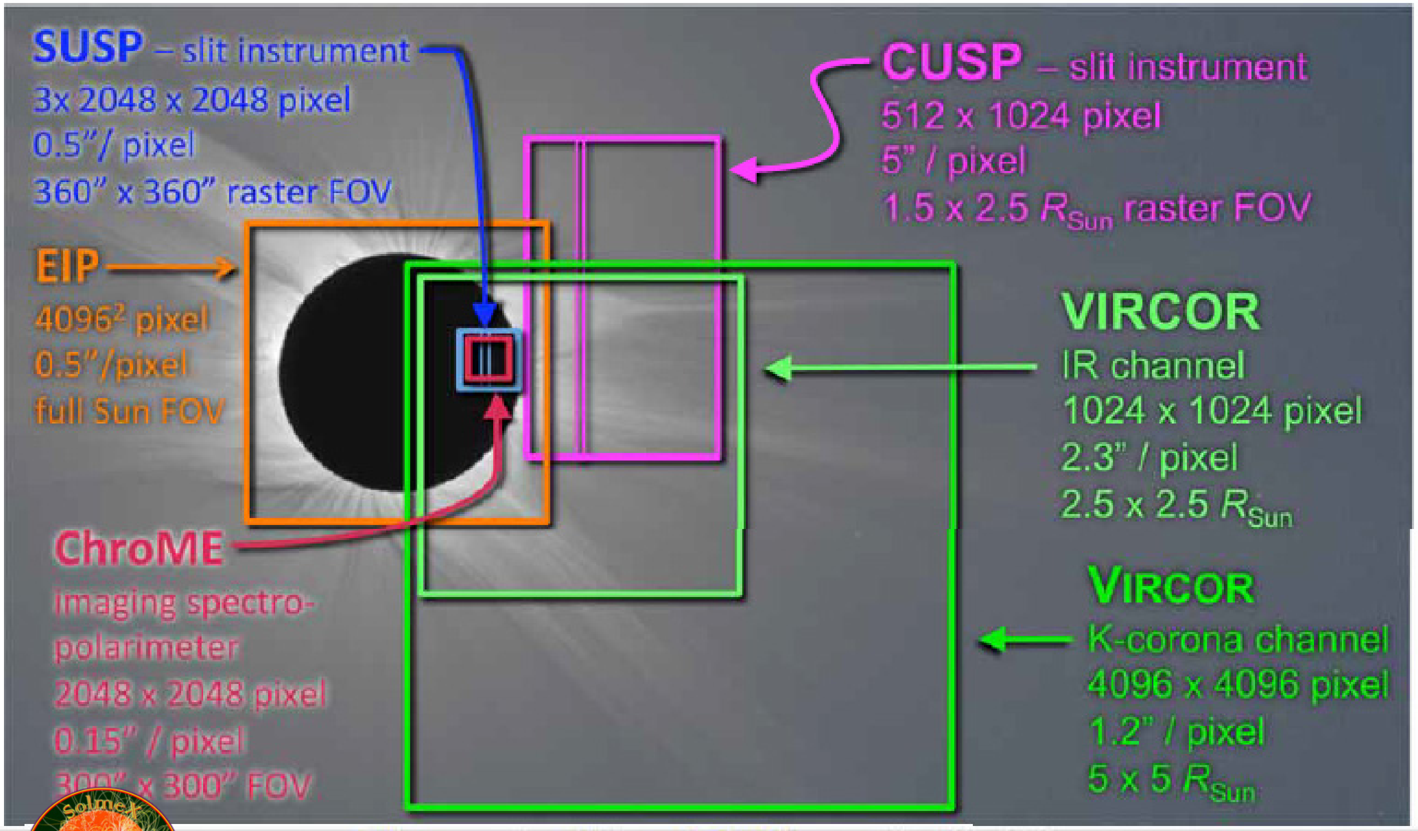
What is SolmeX: Solar Magnetism Explorer

on-disk:

EIP (EUV imaging polarimeter)
SUSP (Scanning UV spectro-polarimeter)
ChroME (Chromospheric magnetic explorer)

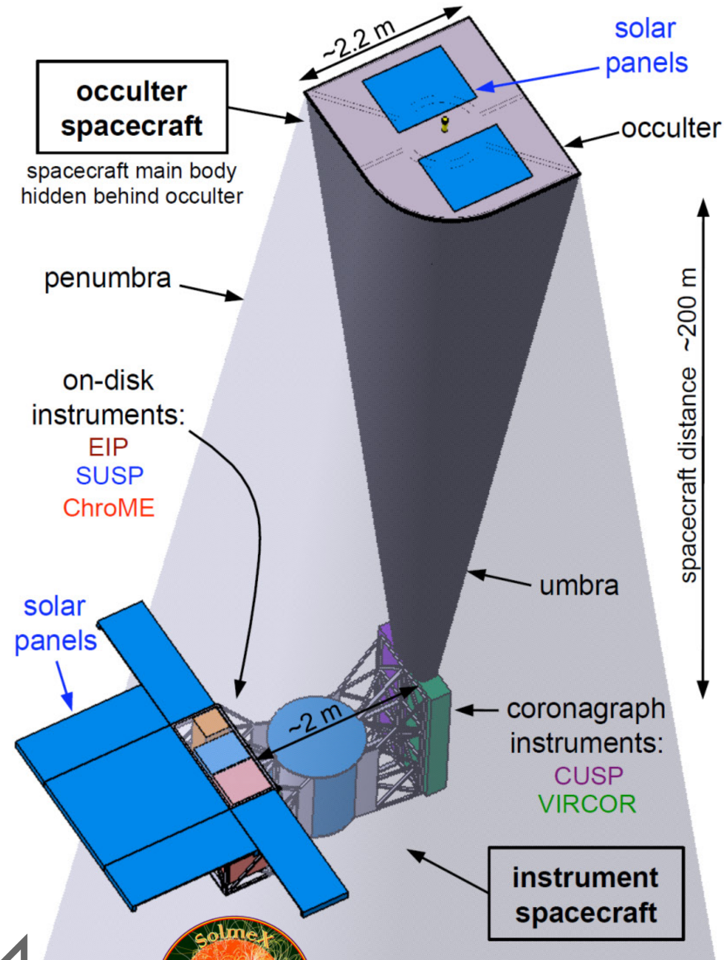
off-limb:

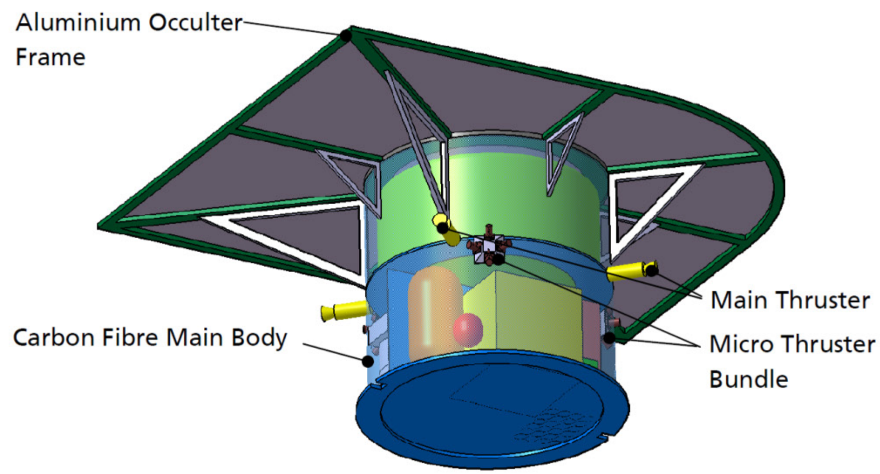
CUSP (Coronal UV spectro-polarimeter)
IRCOR (Visible light and IR coronagraph)

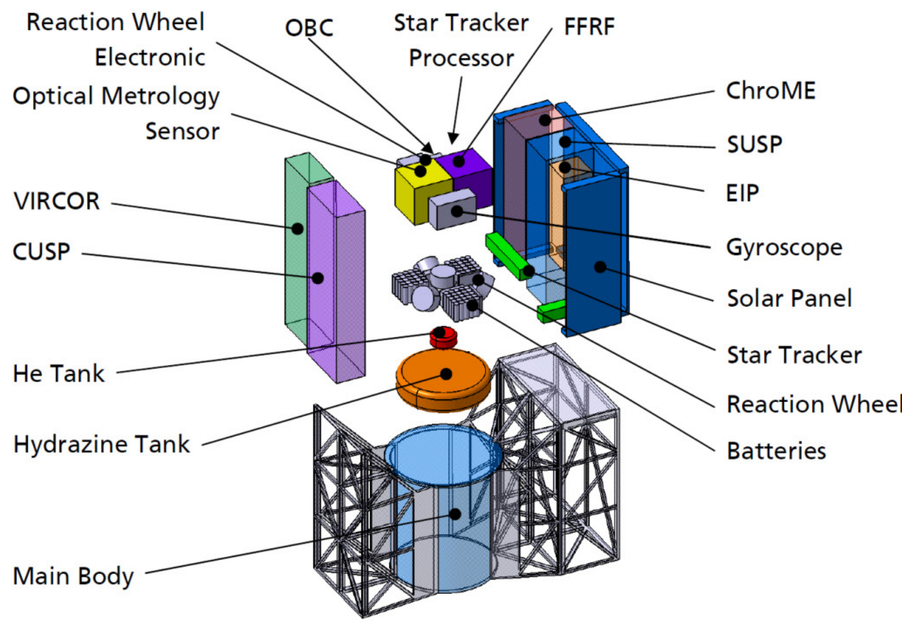


SolmeX CE Study

What is SolmeX: Solar Magnetism Explorer





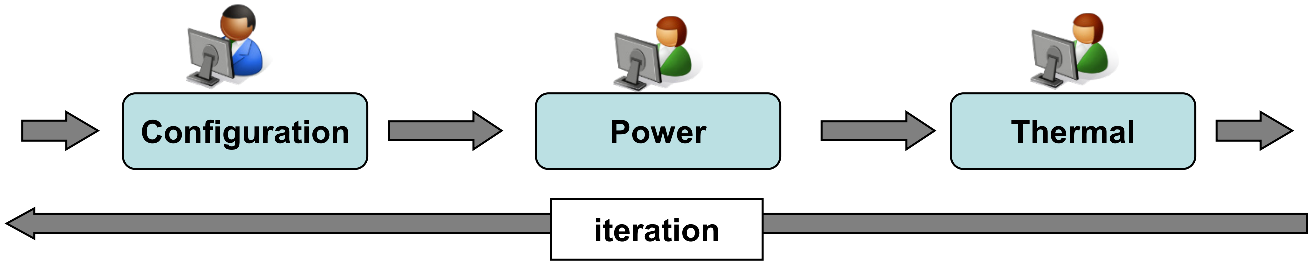


SolmeX CE Study

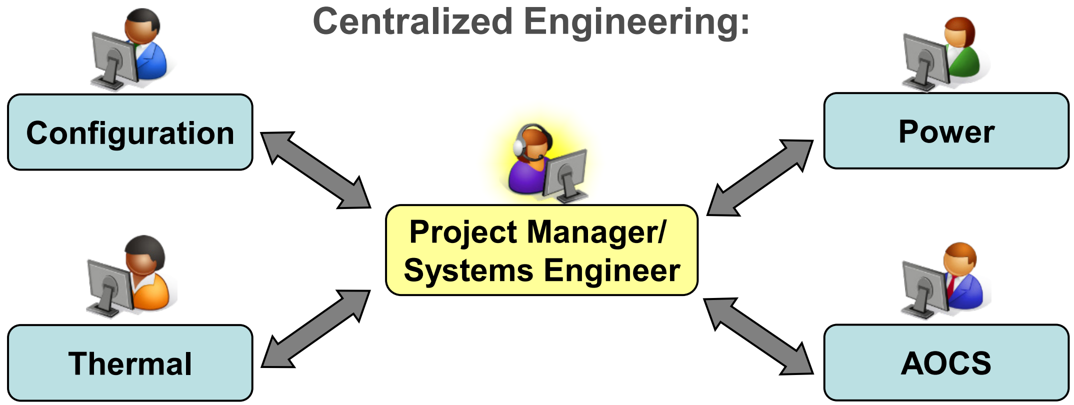
Concurrent Engineering …is <u>not</u>…

- **Conventional Design / Engineering Processes**

Sequential Engineering (with iterations):

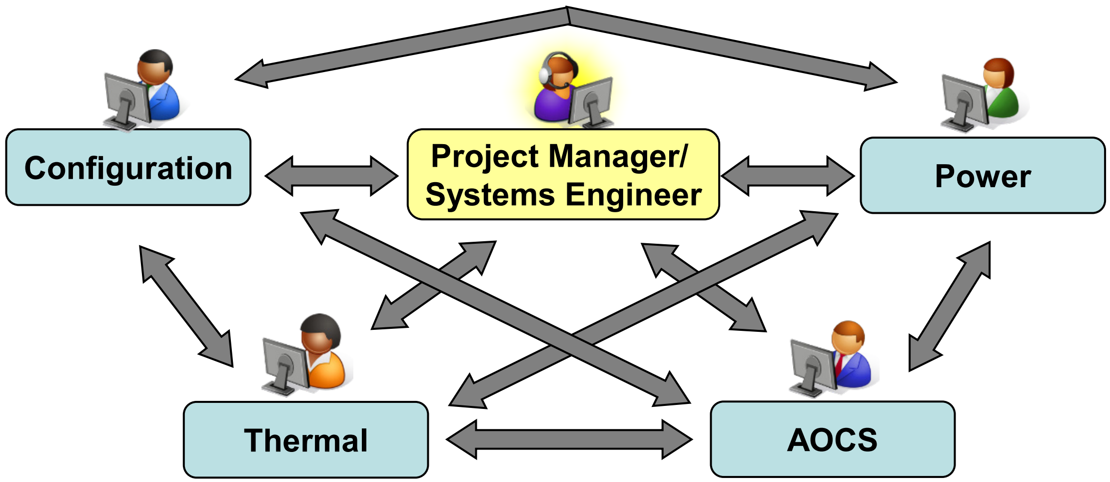


Centralized Engineering:



SolmeX CE Study
…but Concurrent Engineering is…

- Concurrent Design / Engineering Process



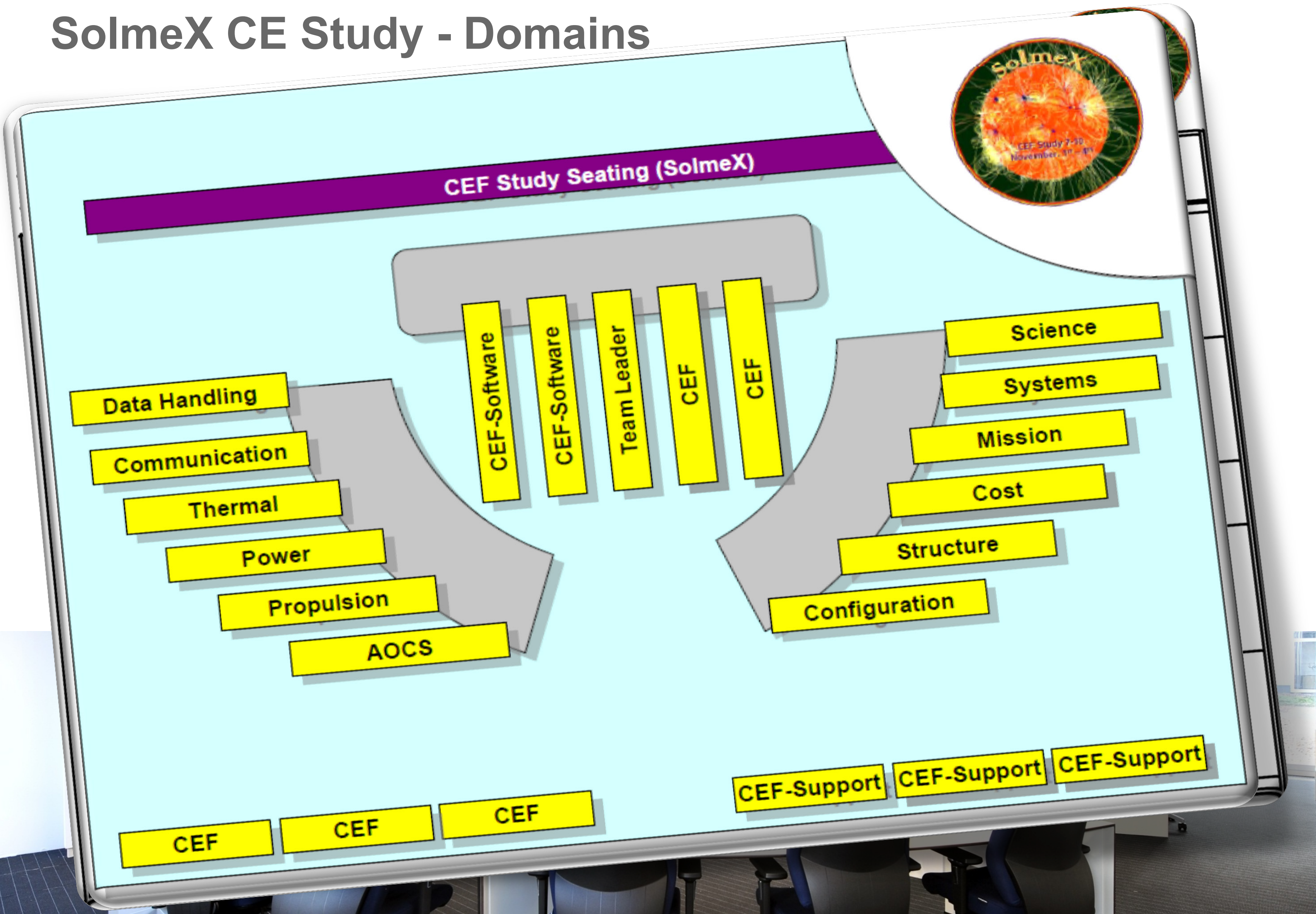
- The five key elements:
  - Interdisciplinary expert team
  - Moderated CE - process
  - Integrated design model
  - Facility / infrastructure
  - Tools (e.g. S/W; multi-media)

SolmeX CE Study - Schedule

SolmeX CEF Study Schedule CW44-10

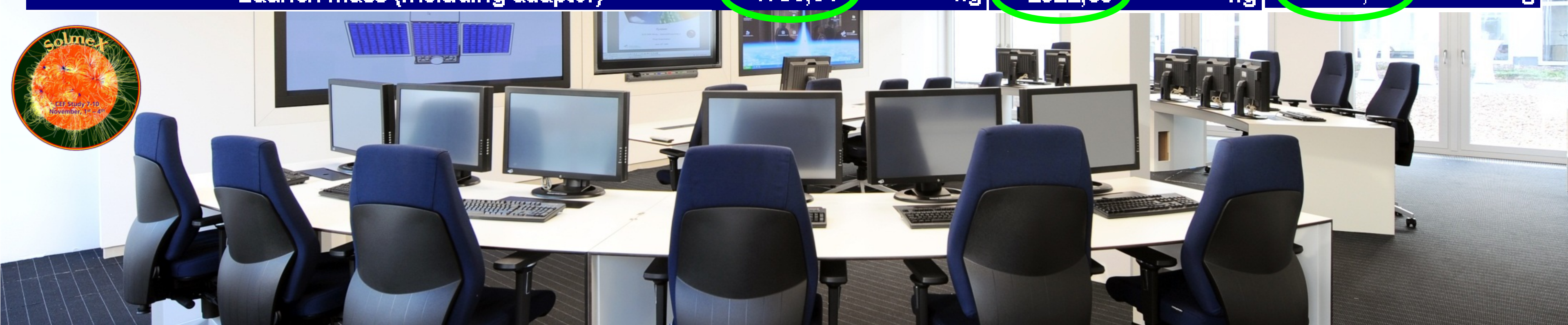
	Monday 01.11.2010	Tuesday 02.11.2010	Wednesday 03.11.2010	Thursday 04.11.2010
09:00 10:00	Arrival	Postprocessing	Session 3 (Start: 09:30)	Session 4 (Start: 09:30)
11:00 12:00	Kick-off Presentations	Session 2		Final Presentations
13:00	Lunch			
14:00 15:00	Session 1	Session 2	Postprocessing / Final Presentation Preparation	Final Presentations
16:00 17:00		Postprocessing		Departure

SolmeX CE Study - Domains



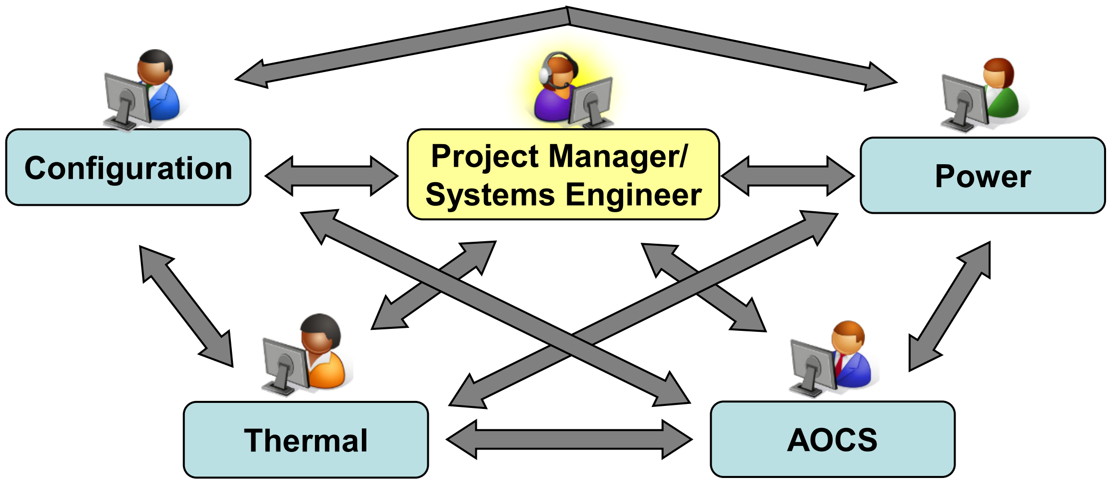
SolmeX CE Study
Subsystem Mass Budget of the CS

	Input Mass	Input Margin	Dry mass contributions	Session #1 Total kg	Session #1 % of Total	Session #2 Total kg	Session #2 % of Total	Session #3 Total kg	Session #3 % of Total
DI	450,00		Structure	450,00	37,71	450,00	37,37	450,00	45,12
EL			Thermal Control	30,00	2,51	35,00	2,91	32,71	3,28
EL			Communications	27,84	2,33	27,84	2,31	20,90	2,10
EL			Data Handling	4,40	0,37	4,40	0,37	7,70	0,77
EL			AOCS	33,50	2,81	61,10	5,07	71,18	7,14
EL			Propulsion	37,13	3,11	294,36	24,45	53,69	5,38
SST			Power	300,00	25,14	20,88	1,73	50,75	5,09
EL			Harness	19,00	1,59	19,00	1,58	19,00	1,90
EL			Instruments	291,48	24,43	291,48	24,21	291,48	29,22
			Total Dry(excl.adapter)	1193,34	kg	1204,05	kg	997,41	kg
			System margin (excl.adapter)	238,67	kg	240,81	kg	199,48	kg
			Total Dry with margin (excl.adapter)	1432,01	kg	1444,86	kg	1196,89	kg
			Other contributions						
			Wet mass contributions						
DI	230,00		Propellant	264,00	15,57	478,00	24,86	230,00	16,12
			Adapter mass (including sep. mech.), kg	100,00	0,06	100,00	0,05	100,00	0,07
			Total wet mass (excl.adapter)	1696,01	kg	1922,86	kg	1426,89	kg
			Launch mass (including adapter)	1796,01	kg	2022,86	kg	1526,89	kg



SolmeX CE Study
…but Concurrent Engineering is…

- Concurrent Design / Engineering Process

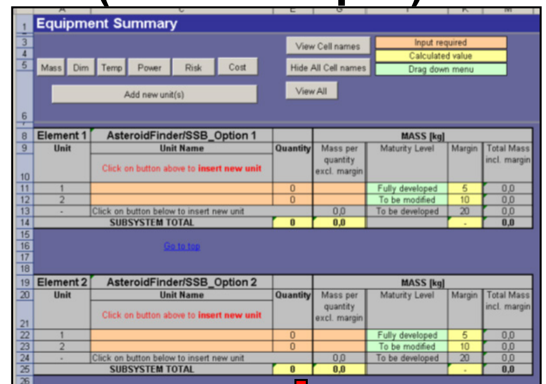


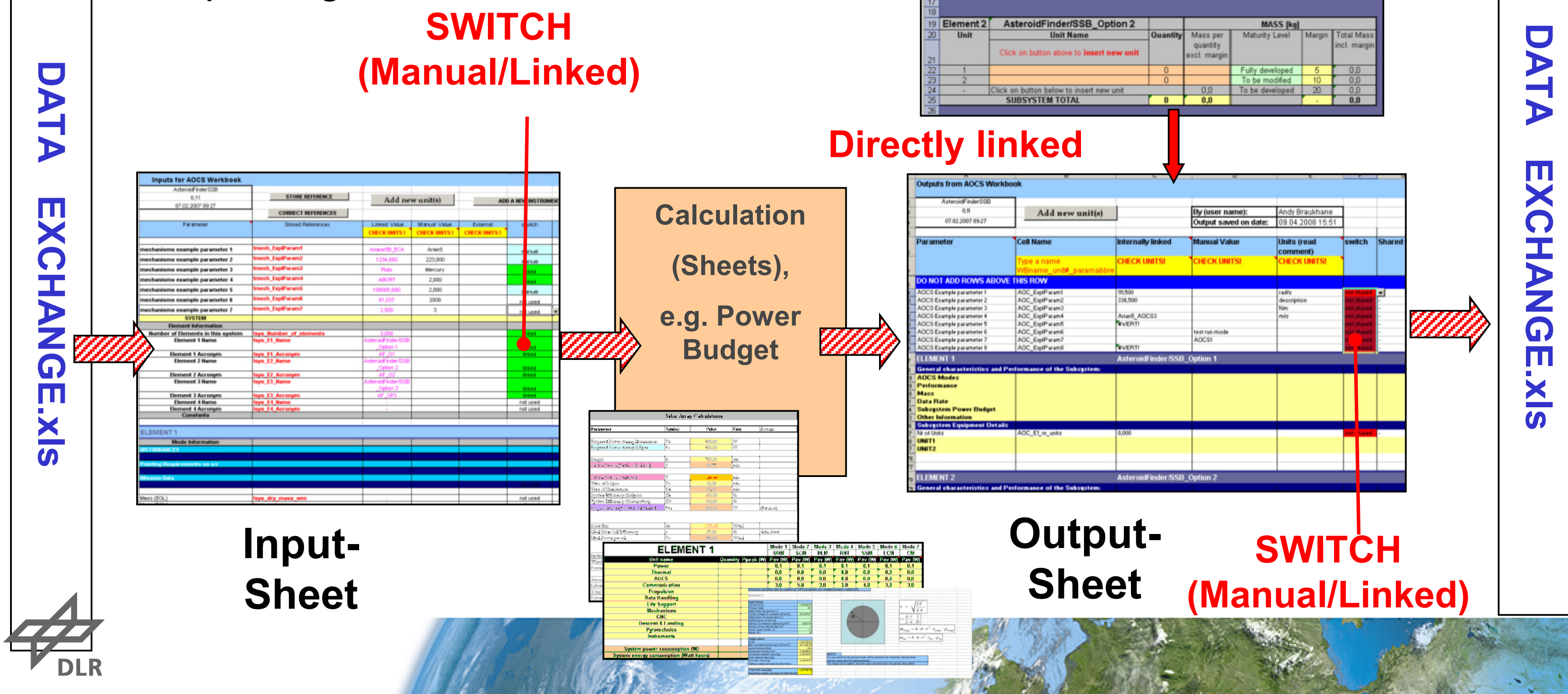
- The five key elements:
  - Interdisciplinary expert team
  - Moderated CE - process
  - **Integrated design model**
  - Facility / infrastructure
  - Tools (e.g. S/W; multi-media)

SolmeX CE Study
Integrated Design Model

- At date of study (2010) we used ESA's CDF Integrated Design Model (IDM):
  Collection of domain specific MS Excel workbooks linked via data exchange and data parking macros

EQ Summary (manual input)





“Main Parameters”

- Explicitly entered to the data model:
  - Mass
  - Dimension
  - Temperature
  - Power
- Summed up to systems level:
  - Total Mass
  - Total Power demand (dependent on mode/duty cycle)

e.g. Propulsion Subsystem EQ Summary:

Equipment Summary

Mass | Dim | Temp | Power | Risk | Cost

View Cell names

Hide All Cell names

View All

Add new unit(s)

Input required

Calculated value

Drag down menu

Element 1	SolmeX Coronagraph Spacecraft		MASS [kg]			
Unit	Unit Name Click on button above to **insert new unit**	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	CHT 10 Thruster	12	0,2	Fully developed	5	3,0
2	N2H4 Tank	1	29,6	To be developed	20	35,6
3	Helium Tank	1	1,1	To be developed	20	1,4
4	He pressuration	1	0,5	Fully developed	5	0,5
5	Heater	1	0,1	Fully developed	5	0,1
6	Valve	1	0,1	Fully developed	5	0,1
-	Click on button below to insert new unit		0,0	To be developed	20	0,0
	SUBSYSTEM TOTAL	**6**	**34,3**		**18,4**	**40,7**

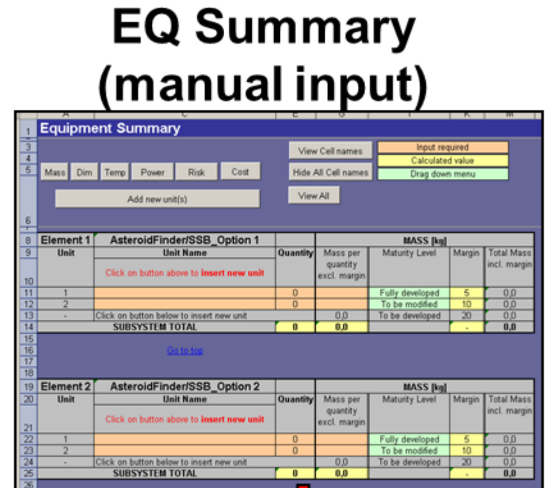
Go to top

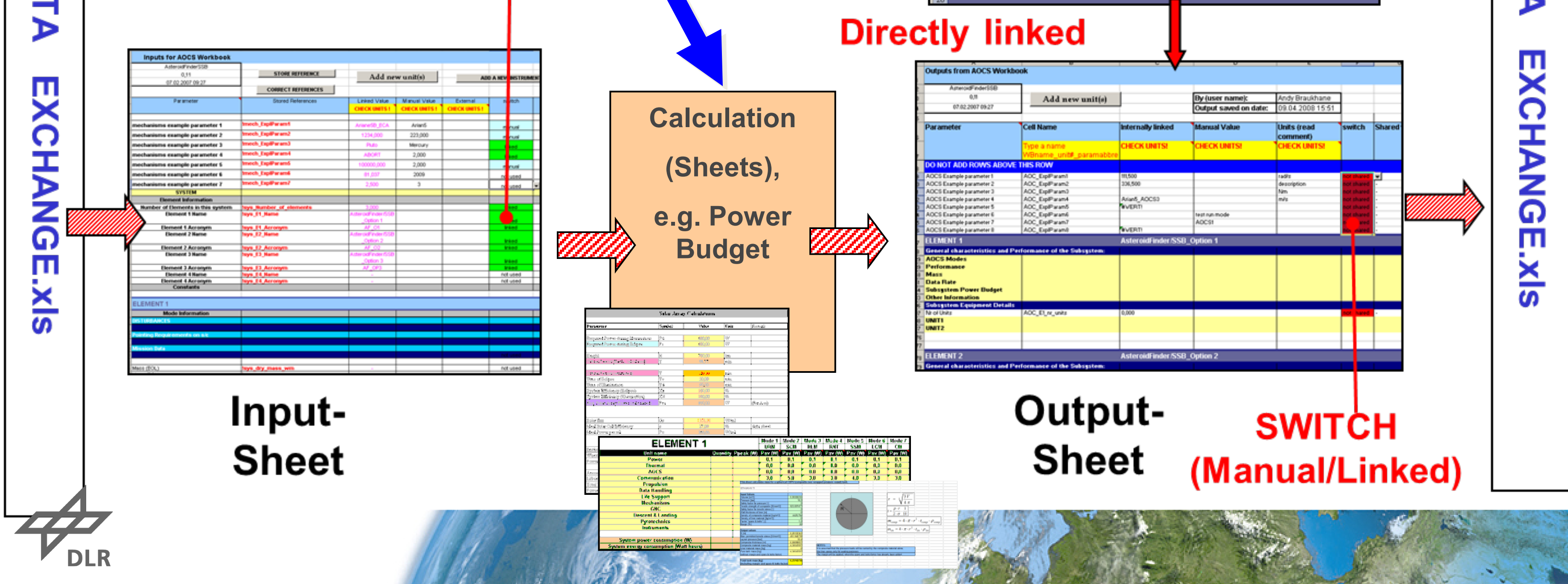
Element 2	-		MASS [kg]			
Unit	Unit Name Click on button above to **insert new unit**	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Helium Tank	1	0,8	To be developed	20	0,9
2	Propellant Tank	1	12,1	To be developed	20	14,6
3	CHT 10 Thruster	6	0,2	Fully developed	5	1,5
4	Cold Gas Tank	1	113,8	To be developed	20	136,6
5	N2 Propellant	1	0,0	Fully developed	5	0,0
6	He pressuraration	1	0,8	Fully developed	5	0,8
7	N2 thruster	12	0,2	Fully developed	5	2,5
8	N2H4 Heater	1	0,1	Fully developed	5	0,1
9	N2H4 Valve	1	0,1	Fully developed	5	0,1
-	Click on button below to insert new unit		0,0	To be developed	20	0,0
	SUBSYSTEM TOTAL	**9**	**131,5**		**19,5**	**157,1**

Go to top

“Implicit Parameters”

- Domain specific parameters:
  - Calculated outside the data model
  - Or via “self-made” calculation sheets





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"Main vs. Implicit Parameters"

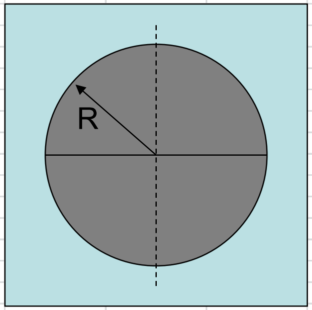
- e.g. Propulsion Subsystem:
  - Components:
    - Thruster
    - Tank → Main Parameters: Tank Mass, Dimensions, Temperature
    - Heater
    - Valve

This sheet calculates mass for a spherical COPV (composite over wrapped pressure vessel) tank.

STA 6Al-4V Ti

Input Values	
Volume [m^3]	0,09326235
Pressure [bar]	16,2
Safety factor for pressure [-]	2
Tensile strenght of composite [N/mm^2]	923,897477
Safety factor for tensile stress [-]	2
Wall thickness of liner [m]	0
Density of composite material [kg/m^3]	4428,784
Density of liner material [kg/m^3]	0
Factor "spars & bolts" [-]	1,2
Margin [%]	20

Output values	
R [m]	0,28132343
Max. permitted tensile stress [N/mm^2]	461,948739
Layout pressure [bar]	32,4
Composite thickness [m]	0,00098657
Composite material mass [kg]	4,34543567
Liner material mass [kg]	0
Pure tank mass [kg] (without margin and spars & bolts factor)	4,34543567
Total tank mass [kg] (including margin and spars & bolts factor)	**6,25742736**



$$r = \sqrt[3]{\frac{3V}{4\pi}}$$

$$t = \frac{p \cdot r}{2 \cdot \sigma} \cdot \frac{1}{10}$$

$$m_{comp} = 4 \cdot \pi \cdot r^2 \cdot t_{comp} \cdot \rho_{comp}$$

$$m_{lin} = 4 \cdot \pi \cdot r^2 \cdot t_{lin} \cdot \rho_{lin}$$

NOTES:

It is assumed that the pressure loads will be carried by the composite material alone;
the liner serves only for sealing purposes.
The margin will be applied, when the spars and bolts factor has already been added.

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"Main vs. Implicit Parameters"

$$m_{tank} = 4\,\pi\,r^2\,t\,\rho_{tank} = \frac{3}{20}\cdot\frac{p\rho_{tank}}{\rho_{propellant}\,\sigma}\cdot m_{launch}\left(1-\frac{1}{e^{\left(\Delta v/c\right)}}\right)$$

$$r = \left(\frac{3\,V_{propellant}}{4\,\pi}\right)^{1/3}$$

$$V_{propellant} = \frac{m_{propellant}}{\rho_{propellant}}$$

$$m_{propellant} = m_{launch}\left(1-\frac{1}{e^{\left(\Delta v/c\right)}}\right)$$

$$t = \frac{1}{10}\cdot\frac{p\,r}{2\,\sigma}$$

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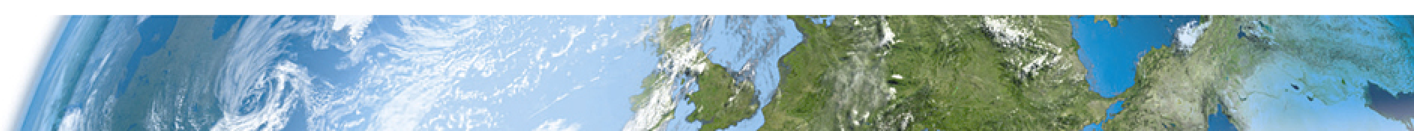

"Main vs. Implicit Parameters"

$$m_{tank} = 4\,\pi\, r^2\, t\, \rho_{tank} = \frac{3}{20} \cdot \frac{p\rho_{tank}}{\rho_{propellant}\,\sigma} \cdot m_{launch} \left(1 - \frac{1}{e^{(\Delta v / c)}}\right)$$

Main Parameter Input	Implicit Parameters	Main Parameter Output
Systems → Launch Mass: m_{launch}	tank pressure p	Propulsion → Tank Mass: m_{tank}
Mission Analysis → Δv	density of tank material ρ_{tank}	Propulsion → Tank Radius: r
	tensile strength of tank material σ	Propulsion → Thickness of Tank Wall: t
	thruster exhaust velocity c	
	density of propellant $\rho_{propellant}$	

→ 10 parameters for tank design + temperature parameters

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Source: Bachelor Thesis
Florian Ruhhammer *

Parameter Graphs - Collection of Study Parameters

Propulsion

$$\left(1 - \frac{1}{e^{(\Delta v / c)}}\right)$$

Power

$$m_{evs\_sp} = A \cdot t \cdot \rho \qquad m_{evs\_sp} = A \cdot F_{spec}$$

Thermal

$$Q_{int} + \alpha \cdot \sigma \cdot T_H^4 \cdot F_p = \sigma \cdot \varepsilon \cdot T^4 \cdot F_{rad}$$

Communication

$$m_{kom} = \psi \cdot (\pi \cdot D^2 \cdot \eta \cdot 0,25) \cdot t \cdot \rho$$

$$GAIN_t = \frac{A_{eff} \cdot (4\pi)}{\lambda^2} \qquad W_f = \frac{P \cdot L_l \cdot G_t \cdot L_a}{4\pi \cdot r_{trans}^2}$$

$$C = \frac{P \cdot L_l \cdot G_t \cdot L_a \cdot D_r^2 \eta}{16 \cdot r^2} \qquad R_{max} = B \cdot log_2 \cdot \left(1 + \frac{C}{N}\right)$$

$$\frac{D \cdot Margin}{F \cdot T_{max} - T_{int}} = B \cdot log_2\left(1 + \frac{C}{N}\right) \qquad R = \frac{D \cdot Margin}{F \cdot T_{max} - T_{int}}$$

$$m_{kom} = \psi \cdot t \cdot \rho \cdot \frac{\lambda^2}{(4\pi)} \left(2^{\frac{D \cdot Margin}{B \cdot F \cdot (T_{max} - T_{int})}} - 1\right) \cdot \frac{N \cdot (4 \cdot \pi \cdot r)^2}{\lambda^2 \cdot P \cdot L_l \cdot L_a \cdot GAIN_r}$$

"…"

* *Untersuchung des Parameterraums einer Concurrent-Engineering-Studie FH Aachen, DLR-Bremen, 2011*

Source: Bachelor Thesis
Florian Ruhhammer

Parameter Graphs - Formulary

i	name	equation	dimension	relations / dependencies
1	coverage / contact times	$A = (P/180°)cos^{-1}(cos\lambda_{max}/cos\lambda)$	[s]	5,44
2	absorbtivity	$P_{\alpha\lambda} = \alpha \cdot S \cdot A_p$	[W]	4,5,6,12,30,36,37,38,44,46 57,64,68,69,71,78,83,89,102,108 113,114,115
3	antenna gain	$G_A = 4\pi\eta A_p/\lambda$		2,4,5,6,7,12,30,33,36,37 38,39,44,46,57,60,64,68,69,83 89,90,98,102,108,113,114,115,118
4	argument of perigee	ω	[°]	
	inclination	i		
			$[m^3]$	2,4,5,6,8,12,18,26,30,36 37,38,42,44,46,57,64,65,68,69 71,78,89,102,103,107,108,114,115
114	true anomaly	υ	[°]	
115	heat flux	$\dot{Q} = \sum f(\Delta T)$	[W/s]	2,4,5,12,26,30,36,37,38,44 46,57,69,71,78,83,89,102,103,107 108,113,114
116	maintenance cycle			
117	angular velocity	$v = \dot{r}$	[m/s]	
118	efficiency	η	[%]	
119	cycle life	$\Delta t = t_{0\_on} - t_{0+1\_off}$	[s]	

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Source: Bachelor Thesis
Florian Ruhhammer

Parameter Graphs – Relations per Parameter per Component

i	Subsystem	Component	Parameter	Relations
	propulsion			
420		tank		
421			mass	16,37,58,79,100,121,126,152,179,233,256 283,301,318,339,358,381,397,412,413,414,415 416,418,422,423,424,425,426,427,428,434
422			housekeeping data	
423			width	1,2,3,4,5,6,7,8,9,11,12 413,414,418,420,423,424,425,426,427,428,429 430,431,432,433,434
424			density	1,2,3,4,8,9,11,12,412,413,414 415,416,418,420,422,424,425,426,427,428,429 430,431,432,433,434
425			shape	3,4,5,6,7,8,9,11,12,413,414 418,422,423,425,426,427,428,429,430,431,432 433,434
426			height	1,2,3,4,5,6,7,8,9,11,12 413,414,418,420,422,423,424,426,428,429,430 431,432,433,434
427			length	1,2,3,4,5,6,7,8,9,11,12 413,414,418,420,422,423,424,425,427,428,429 430,431
			surface	

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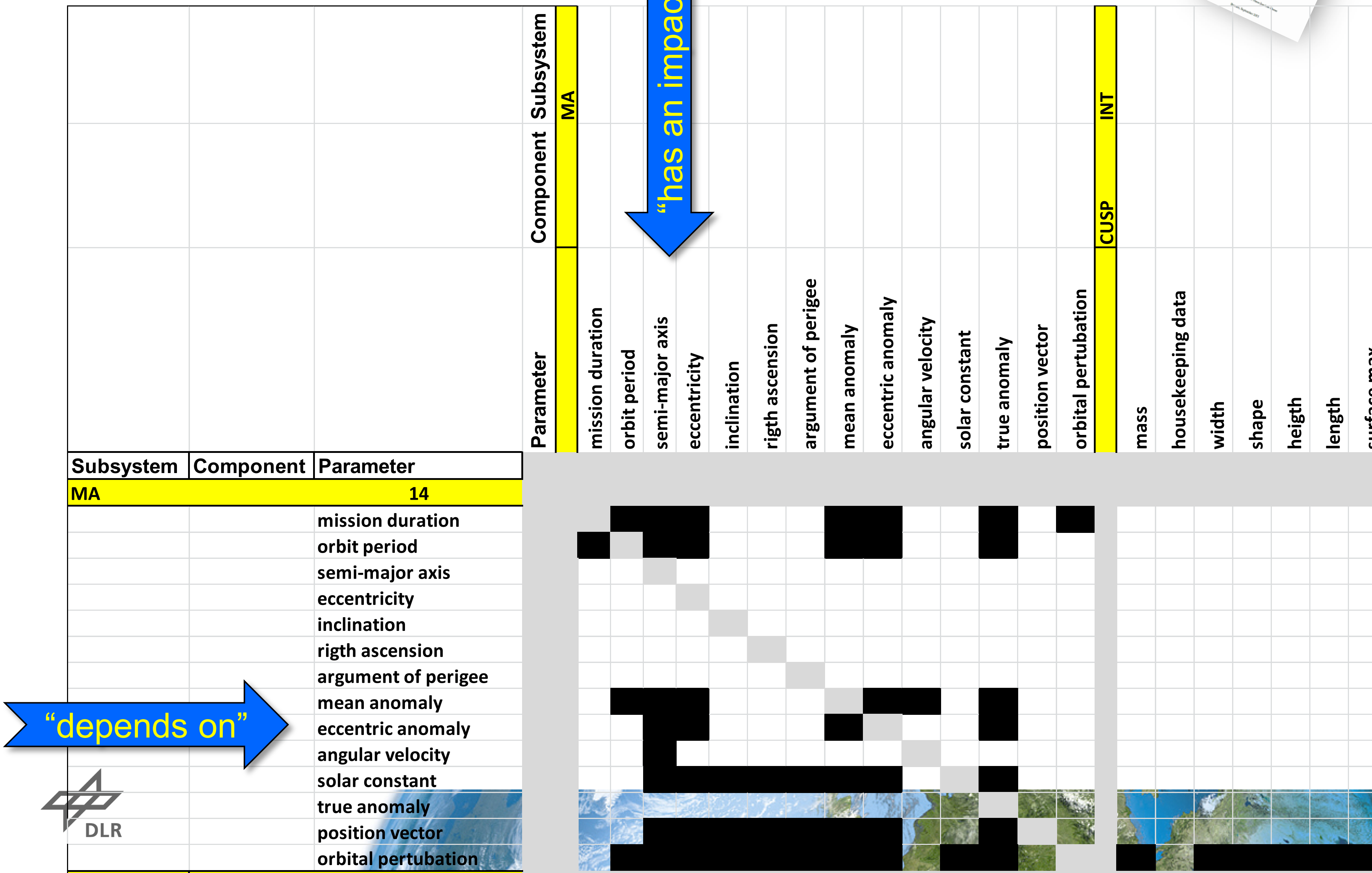
Source: Bachelor Thesis Florian Ruhhammer

Parameter Graphs – Design Structure Matrix (Adjacency Matrix)



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Source: Bachelor Thesis Florian Ruhhammer

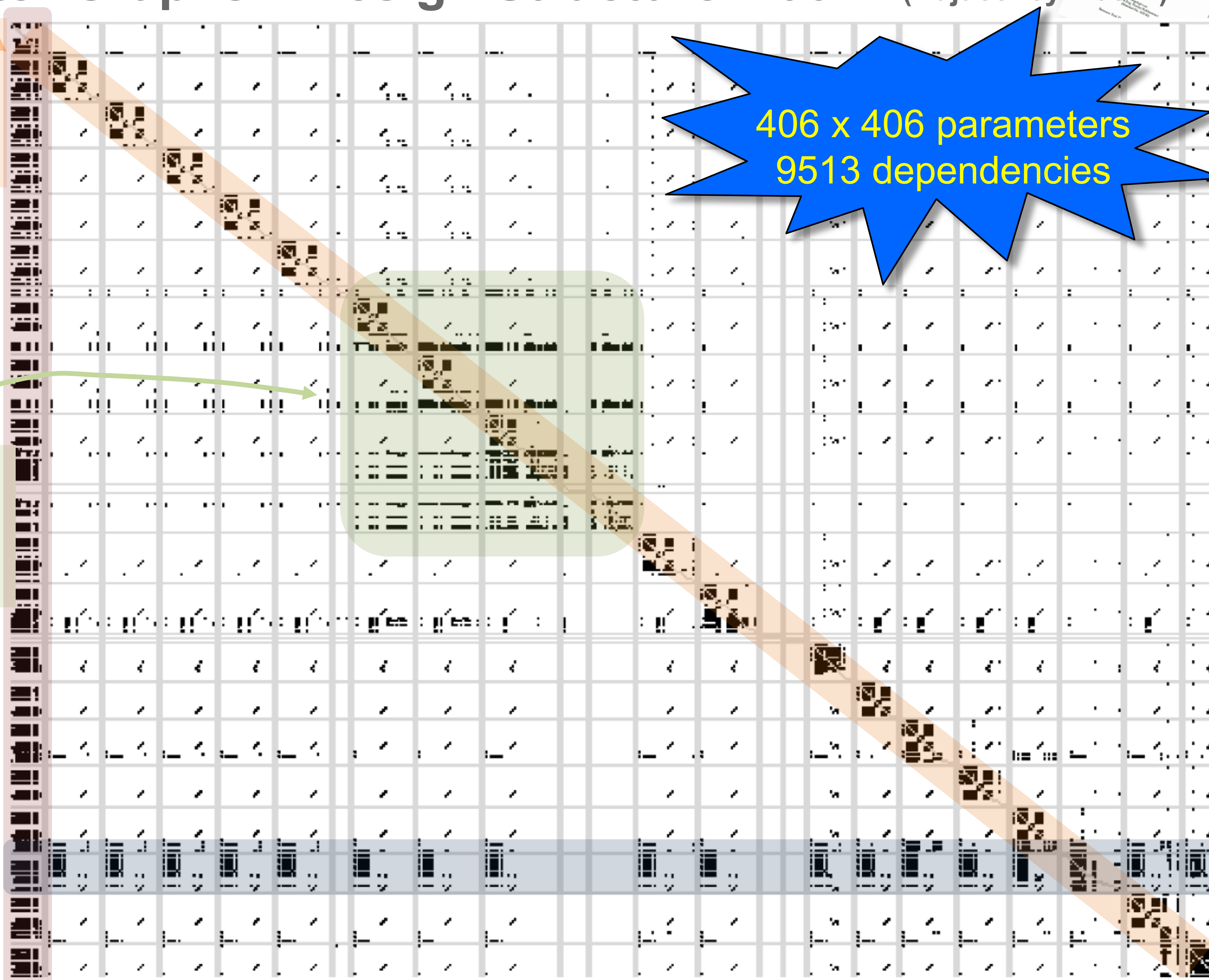
Parameter Graphs – Design Structure Matrix (Adjacency Matrix)

Domain-specific parameters

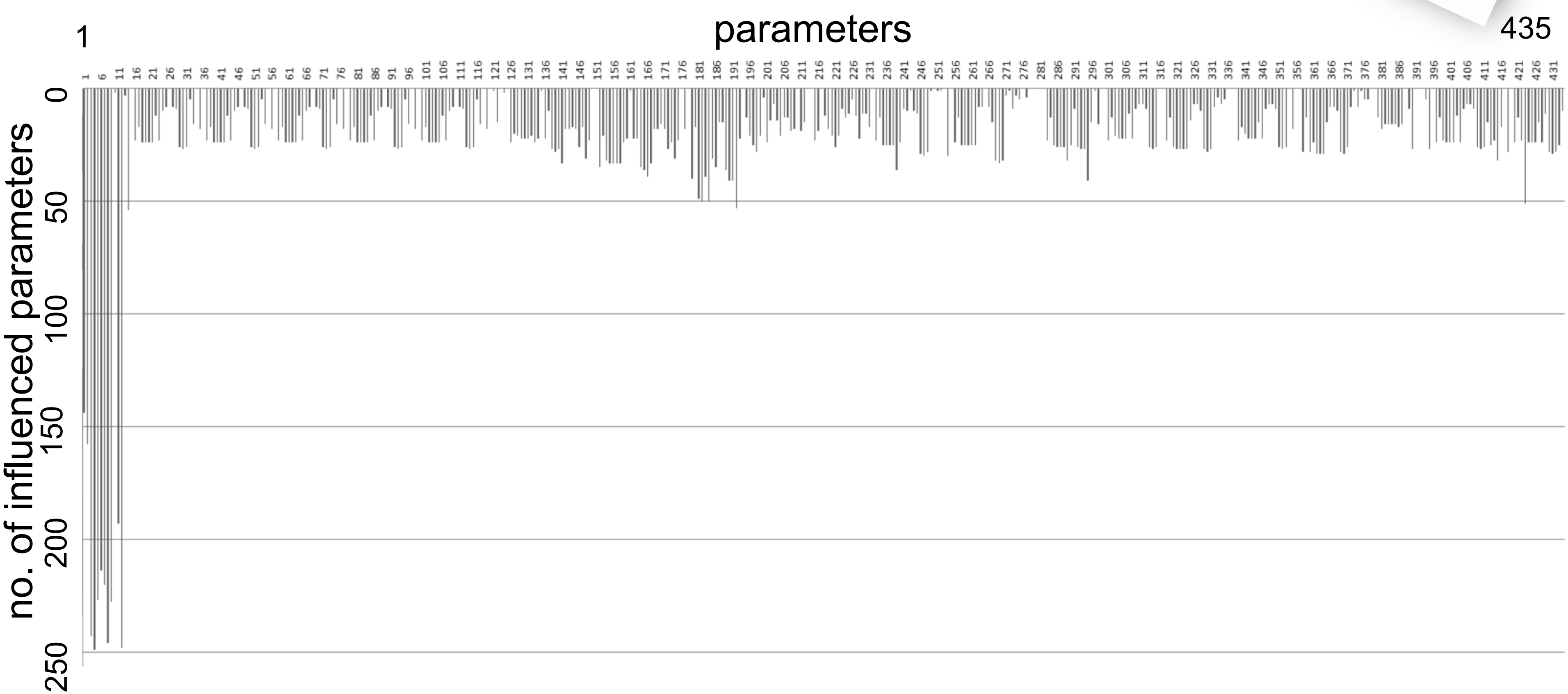
Mission Analysis

Data Handling & Communication

Configuration

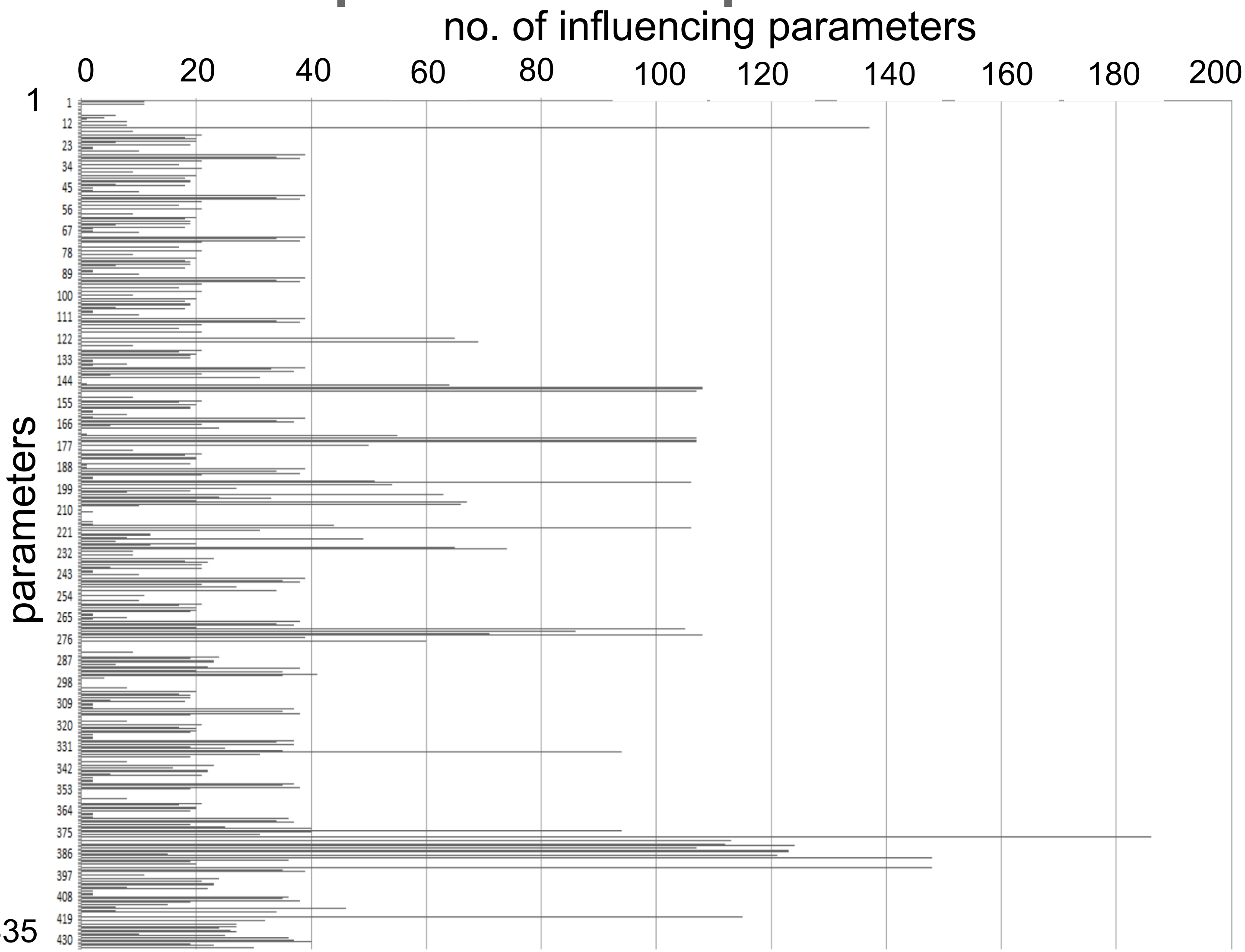


Parameter Graphs – DSM: Impacts



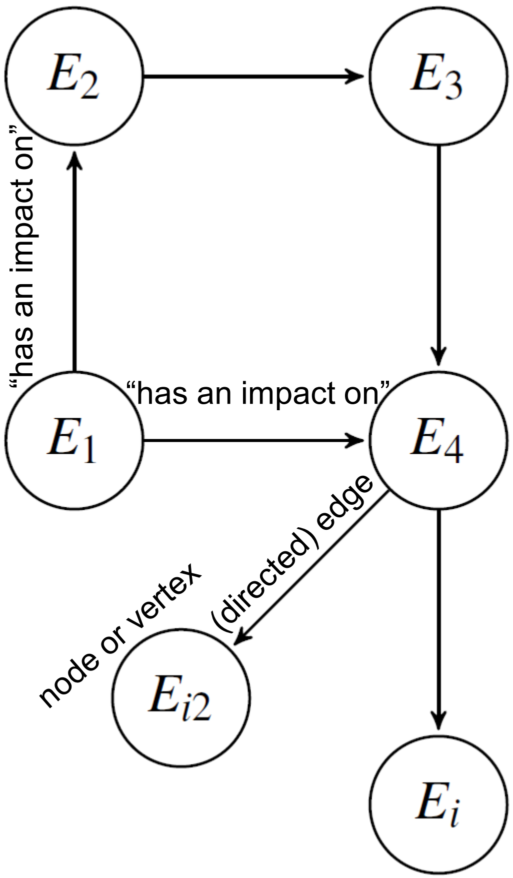
Source: Bachelor Thesis Florian Ruhhammer

Parameter Graphs – DSM: Dependencies



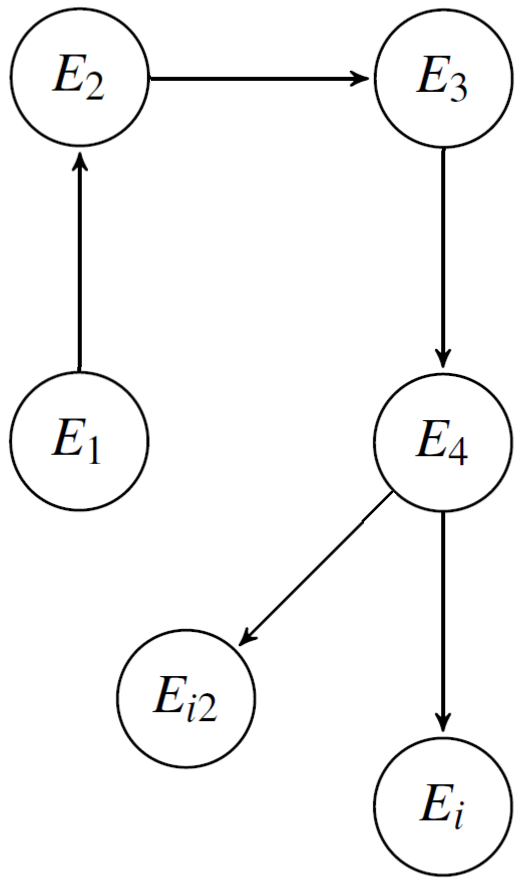
Source: Bachelor Thesis
Florian Ruhhammer

Parameter Graphs



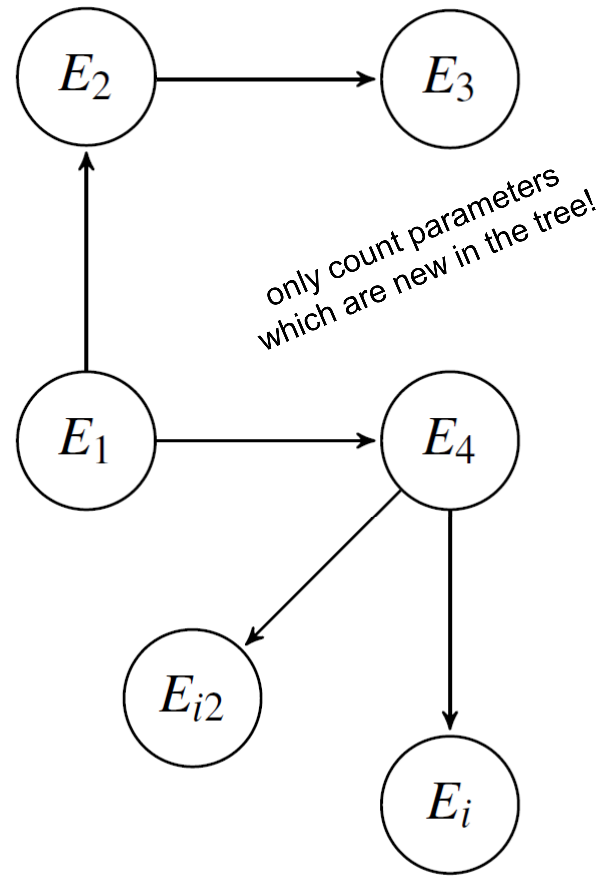
Graph Data Structure

Depth-First Search



Depth: 4

Breadth-First Search



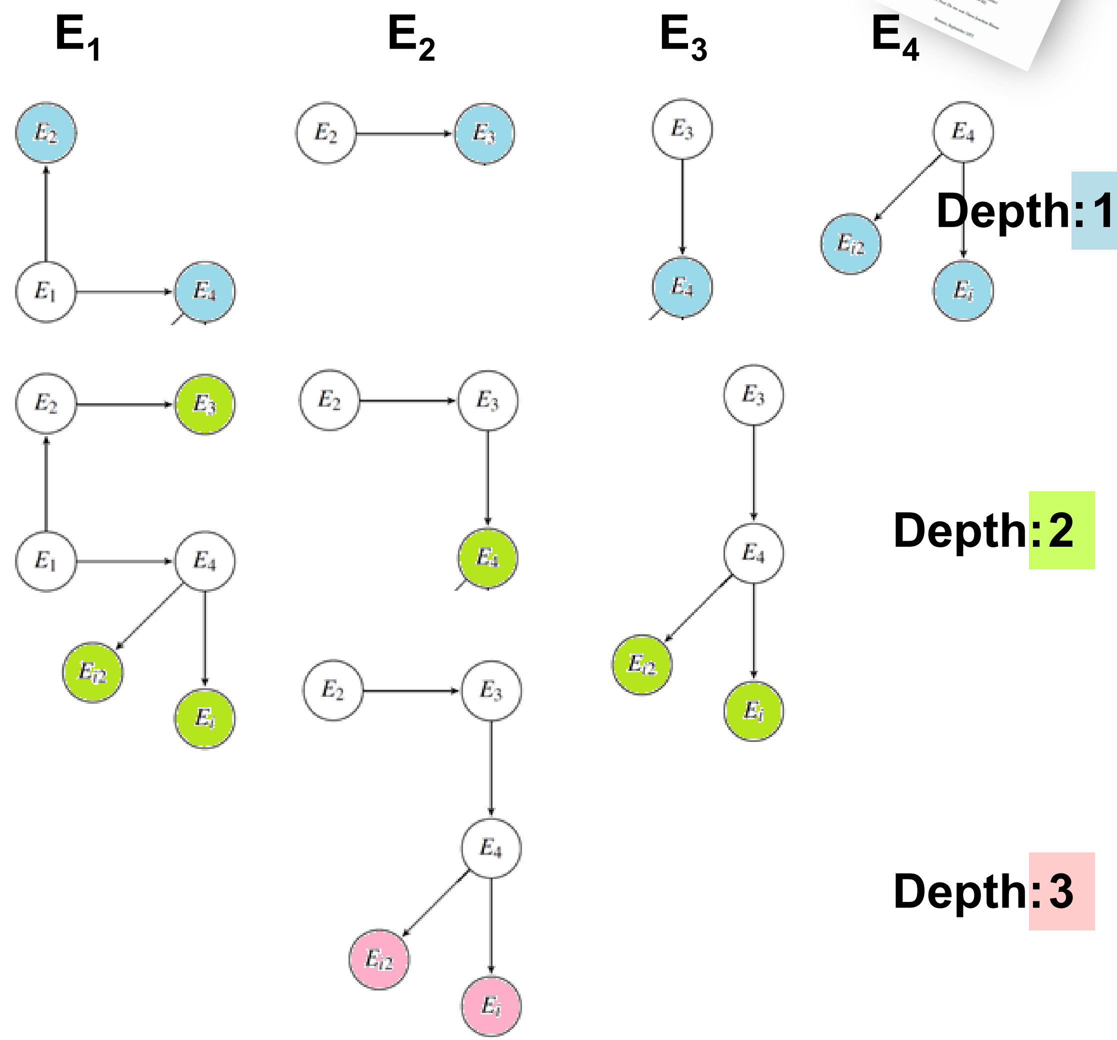
Depth: 2

Source: Bachelor Thesis
Florian Ruhhammer

Parameter Graphs – Impacts on Parameters

(Breadth-First Search)

Depth	Hits Total	Max	Min	Ratio to 1. depth occurrence	Occurrence
1	6	2	1	1.2	5
2	6	2	1	1.2	4
3	2	2	2	0.4	2
4	0	0	0	0	0
Ø2	Ø3.5	5	2	one parameter; all depths	



Source: Bachelor Thesis Florian Ruhhammer

Parameter Graphs – Impacts on Parameters

Sum of Total Hits: 108,800

Depth	Hits Total	Max	Min	Ratio to 1. depth occurrence	Occurrence
1	9513	249	1	25.23	377
2	29583	246	1	78.47	377
3	30691	204	2	81.41	367
4	6699	162	1	17.77	360
5	7689	137	1	20.40	349
6	9778	137	1	25.94	211
7	8334	137	9	22.11	131
8	5045	137	9	13.38	113
9	1149	137	9	3.05	73
10	292	13	7	0.77	32
11	27	9	9	0.07	3
12	0	0	0	0.00	0
Ø6.35	Ø288.59	299	2	(one parameter; all depths)	

Source: Bachelor Thesis Florian Ruhhammer

Parameter Graphs – Parameter Impacts/Dependencies for “Launch Mass”

Sum of Total Hits:
Impact on 296
Dependent on 367

System: $m_{launch} = m_{stucture} + m_{payload} + m_{propulsion} + \cdots$

Subsystem: $m_{propulsion} = m_{thruster} + m_{tank} + \cdots$

Component: $m_{tank} =$

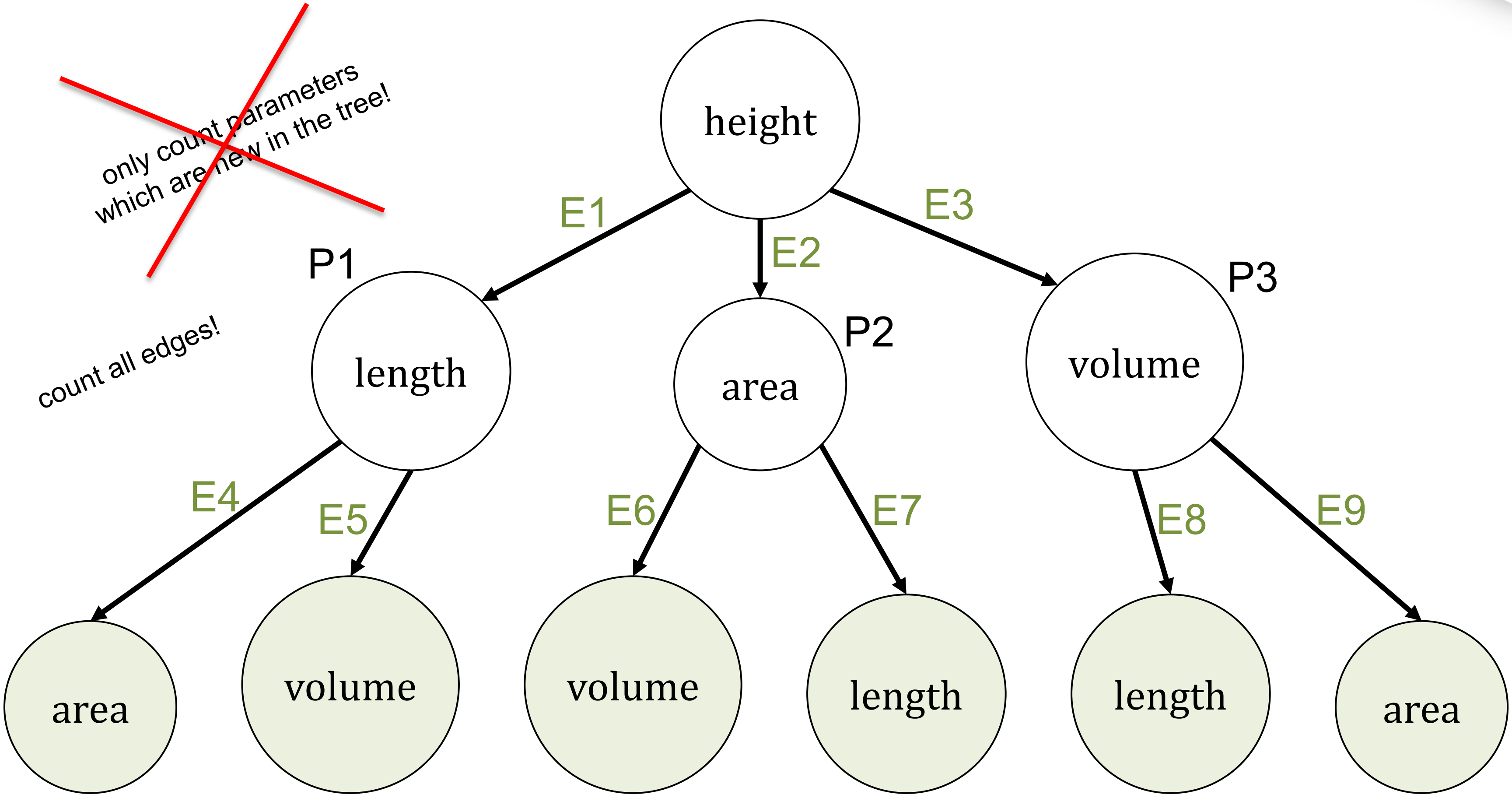
Depth	Impact on	Dependent on
1	28	112
2	59	111
3	183	26
4	15	40
5	11	41
6		31
7		3
8		

Source: Bachelor Thesis
Florian Ruhhammer

Parameter Graphs – Impacts on Directed Edges

~~only count parameters which are new in the tree!~~

count all edges!



Source: Bachelor Thesis Florian Ruhhammer

Parameter Graphs – Impacts on Directed Edges

Sum of Total Hits: 2,595,634

Depth	Hits Total	Max	Min	Ratio to 1. depth occurrence	Occurrence
1	9513	249	1	25.23	377
2	188047	6088	1	498.80	377
3	634509	5831	1	1683.05	376
4	684090	5213	36	1814.56	369
5	182442	3567	24	483.93	362
6	238397	3135	24	632.35	351
7	254914	3127	24	676.16	211
8	207088	3127	228	549.31	131
9	134584	3127	450	356.99	112
10	44021	3123	445	116.77	73
11	16445	528	445	43.62	32
12	1584	528	528	4.20	3
Ø7.36	Ø6884.97	7273	3	(one parameter)	

DLR

Source: Bachelor Thesis
Florian Ruhhammer

Parameter Graphs – Edges Impacts/Dependencies for "Launch Mass"

Sum of Total Hits:
Impact on 7024
Dependent on 8569

Depth	Impact on	Dependent on
1	28	115
2	553	2752
3	1115	2975
4	4248	112
5	516	518
6	564	1089
7		959
8		49

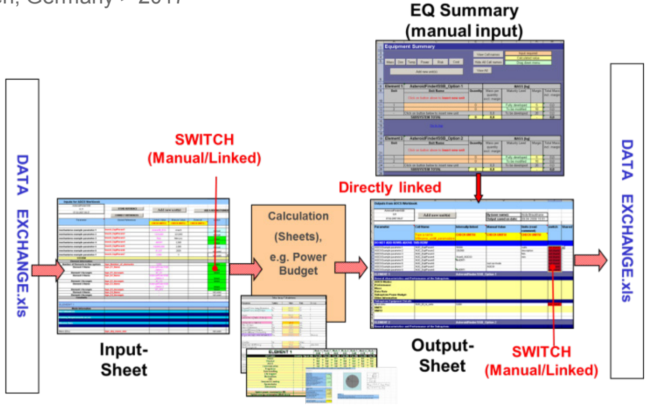
System: $m_{launch} = m_{stucture} + m_{payload} + m_{propulsion} + \cdots$

Subsystem: $m_{propulsion} = m_{thruster} + m_{tank} + \cdots$

Component: $m_{tank} =$

DLR

Discussion – Meaning for MDO



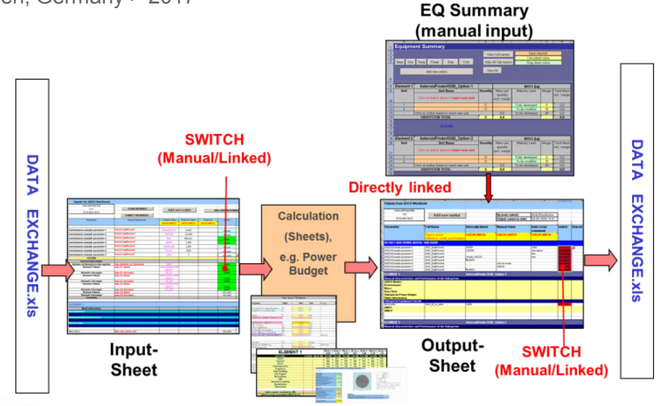
- <u>Assumption regarding the Data Model:</u>
  - So far: only **fixed values** for input/output parameters
  - What if it would be possible to e.g. declare all dependent parameters as **variables within a specific interval** ?! (generic / each study started from scratch)

Min. Launch Mass / Cost
Max. Mission Lifetime
Max. downloaded Science Data

Multidisciplinary Design Optimization task
- 377 variables out of 406 parameters
- 9513 dependencies in the first depth
- 108,800 parameter relations
- 2,595,634 edges

What do you think of with this information ?

Discussion – Meaning for MDO



- Which kind of functions?
  - Linear, exponential, logarithmic, trigonometric
  - Non-convex design space, discontinuous (e.g. different thruster types of fixed thrust: 3 x 10N vs. 1 x 30N)
  - Not always differentiable (no Jacobi/Hesse)
  - Loops between parameters

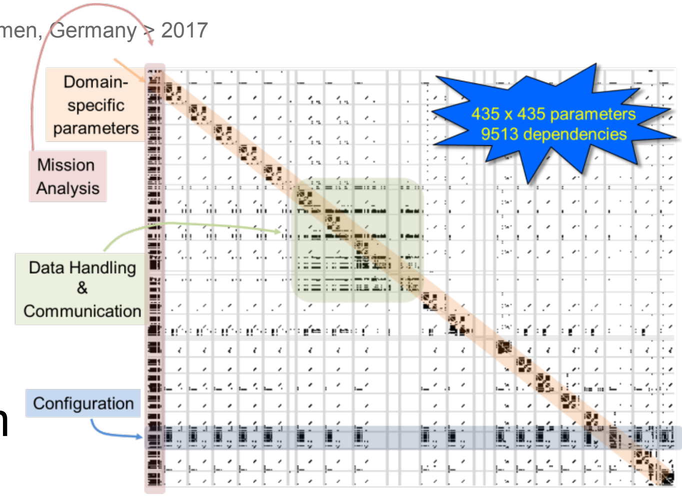
$$m_0 = (m_{max-low} - m_{NUTZ} - m_{SUB}) \cdot (1 - exp^{-\frac{\Delta v}{c}})$$

$$\frac{D \cdot Margin}{F \cdot (T_{max} - T_{int})} = B \cdot log2\left(1 + \frac{P \cdot L_l \cdot GAIN_t \cdot L_a \cdot GAIN_r (\frac{\lambda}{4 \cdot \pi \cdot r})^2}{N}\right)$$

$$P_{el} = S_0 \cdot (\frac{1AU}{r})^2 \cdot A \cdot \eta cos(\varphi)$$

DLR

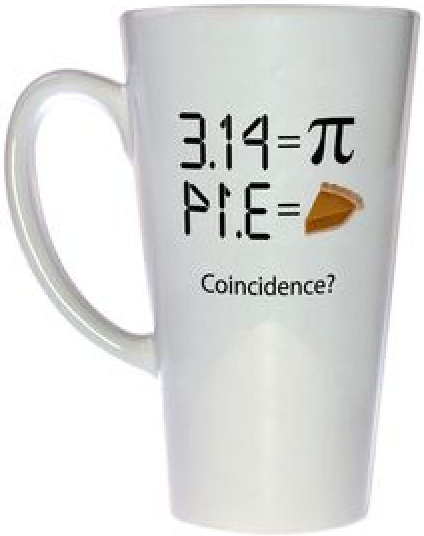
Discussion – Meaning for MDO



- Domain specific blocks could be used as a problem decomposition and be simplified via curve fitting techniques
- Exclude Configuration parameters since they are more dependent than having impacts on others
- Sensitivity analysis upstream the optimization in order to neglect variables which have low influence on the total system or objective function
- Interval arithmetic for knowing the feasible solution interval

What do you think of with this information ?

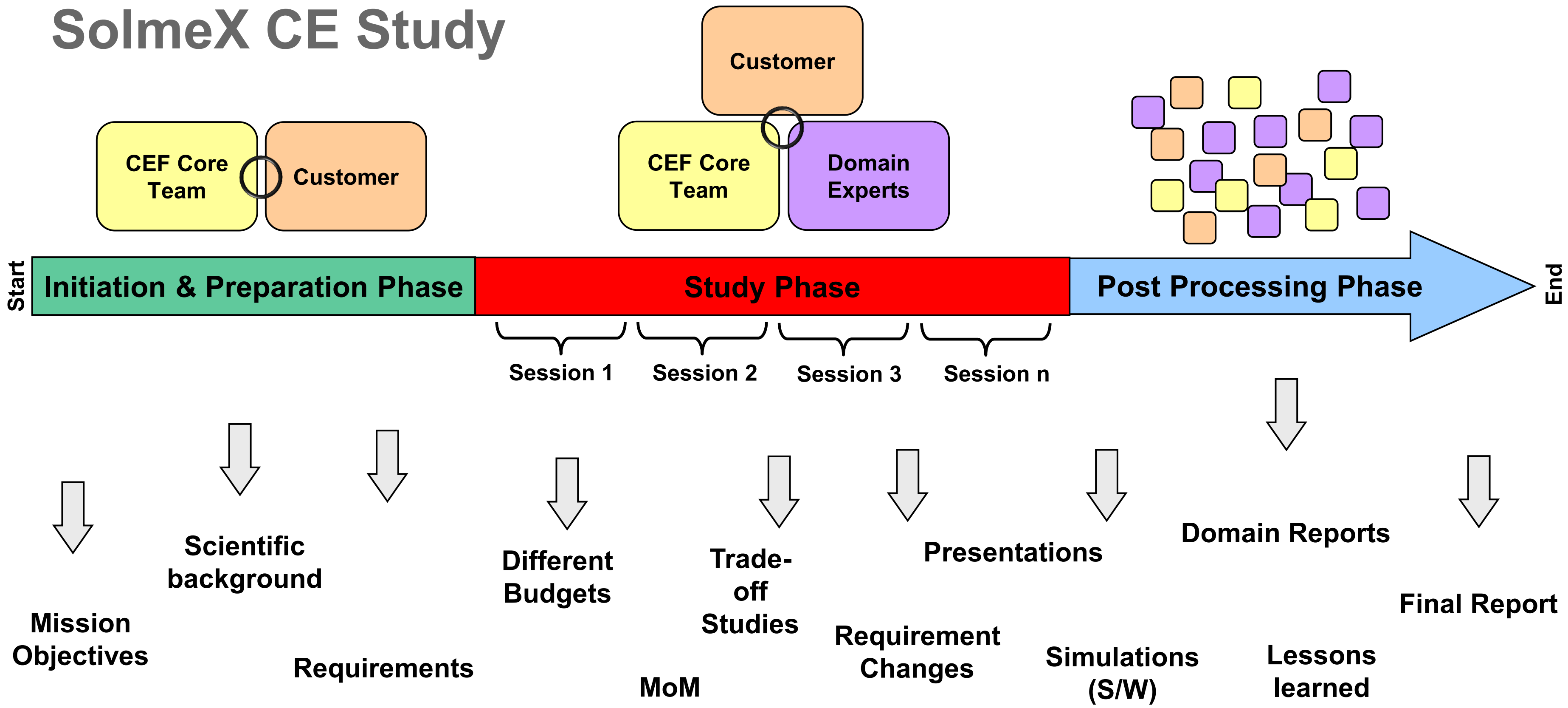
Thank you and enjoy the coffee break!



OPTIMISATION IN SPACE ENGINEERING

Backup Slides

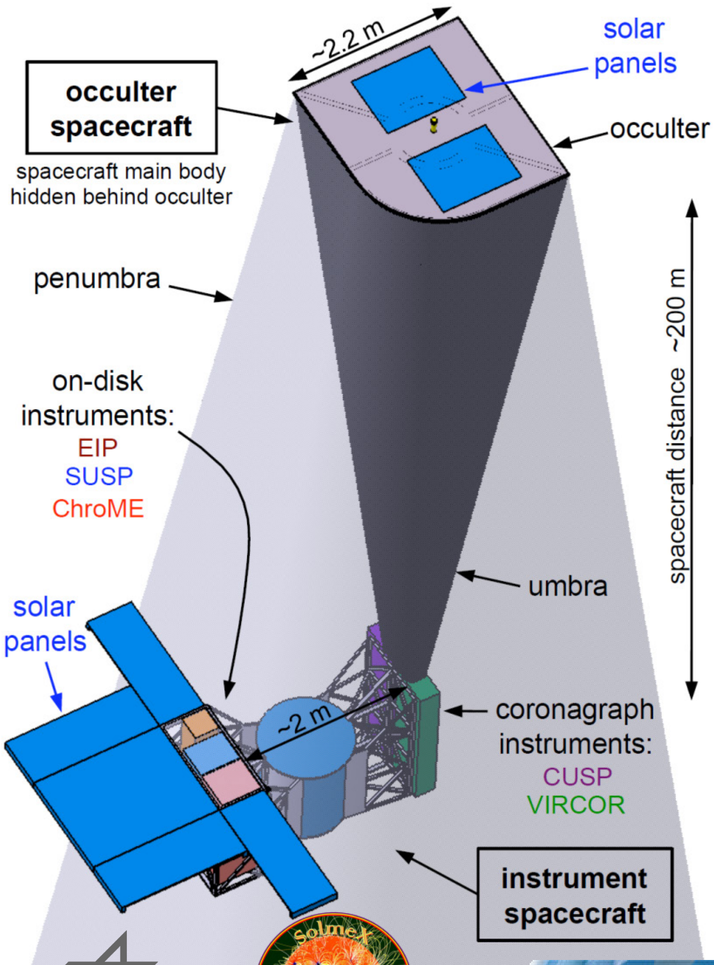
SolmeX CE Study

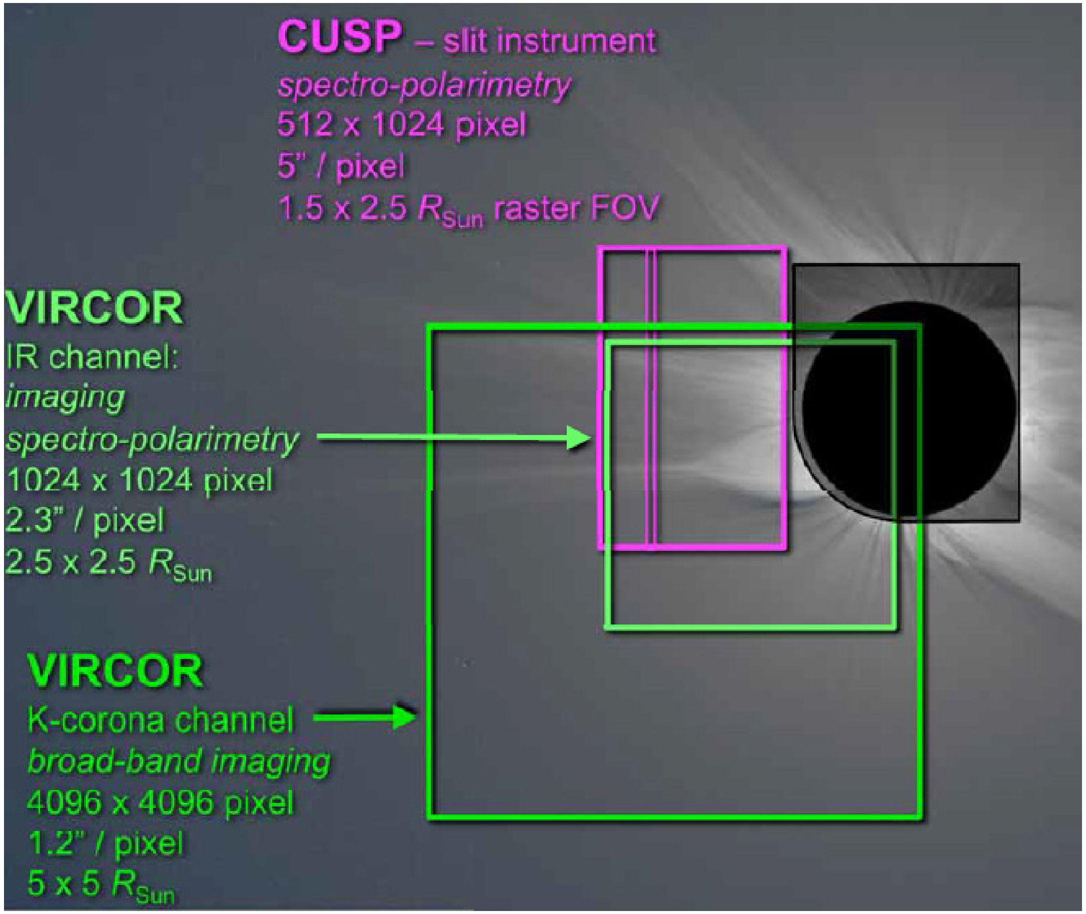


SolmeX CE Study
What is SolmeX? - Science Background -

- What is the magnetic structure of the outer solar atmosphere?
- What is the nature of the changes of the magnetic field over the solar cycle?
- What drives large-scale coronal disruptions such as flares and coronal mass ejections?
- How do magnetic processes drive the dynamics and heating of the outer solar atmosphere?
- How does the magnetic field couple the solar atmosphere from the photosphere to the corona?

SolmeX CE Study
What is SolmeX: Solar Magnetism Explorer





Parameter Graphs – Launch Mass

$$m_0 = (m_{max-low} - m_{NUTZ} - m_{SUB}) \cdot (1 - exp^{-\frac{\Delta v}{c}}) \quad (3.80)$$

$$= \Big\{ m_{max-low} \quad (3.81)$$

$$-(m_{CHroME} + m_{CUSP} + m_{SUSP} + m_{EIP} + m_{VIRCOR})_{nutz} \quad (3.82)$$

$$-\Big[(m_{cpu} + m_{massenspeicher})_{dvs} \quad (3.83)$$

$$+\Big\{ \Big[\psi \cdot t \cdot \rho \cdot \frac{\lambda^2}{(4\pi)} \left(2^{\frac{D \cdot Margin}{B \cdot F \cdot (T_{max} - T_{int})}} - 1 \right) \cdot \frac{N \cdot (4 \cdot \pi \cdot r)^2}{\lambda^2 \cdot P \cdot L_l \cdot L_a \cdot GAIN_B} \Big]_{uplink} \quad (3.84)$$

$$+ \Big[\psi \cdot t \cdot \rho \cdot \frac{\lambda^2}{(4\pi)} \left(2^{\frac{D \cdot Margin}{B \cdot F \cdot (T_{max} - T_{int})}} - 1 \right) \cdot \frac{N \cdot (4 \cdot \pi \cdot r)^2}{\lambda^2 \cdot P \cdot L_l \cdot L_a \cdot GAIN_B} \Big]_{downlink} \Big\}_{kom} \quad (3.85)$$

$$+ \Big[F_{spec} \cdot \frac{(P_{evs\_DVS} + P_{evs\_KS} + P_{evs\_EVSEigen} + P_{evs\_TS} + P_{evs\_LBS} + P_{evs\_SIMK} + P_{evs\_AS}) \cdot r^2}{S_0 \cdot \eta \cdot cos\phi \cdot AU^2} \quad (3.86)$$

$$\cdot \frac{P_{evs\_el} \cdot t \cdot 100 \cdot (-0,0272)}{3600 \cdot \eta \cdot [ln(CL) - ln(207800)] \cdot E_{spc}} \Big]_{evs} \quad (3.87)$$

$$+ \Big[F_{spez} \cdot \frac{Q_{int} + \alpha \cdot \sigma \cdot (\frac{P_{S,i}}{\sigma \varepsilon F} + \frac{P_{A,i}}{\sigma \varepsilon F} + \frac{P_{IR,i}}{\sigma \varepsilon F} - \frac{\sum r_{ij}(T_j^4 - T_i^4)}{\varepsilon F}) \cdot F_p}{\sigma \cdot \varepsilon \cdot T^4} + m_{heiz} \Big]_{ts} \quad (3.88)$$

$$+ (m_{dral} + m_{gyr} + m_{ste})_{lbs} \quad (3.89)$$

$$+ m_{simk} + \Big[m_{due} + 4 \cdot \pi \cdot \frac{3 \cdot V_{komp}}{4 \cdot \pi} \cdot \rho \cdot \frac{p}{20} \Big]_{as} \Big]_{sub} \Big\} \quad (3.90)$$

$$\cdot (1 - exp^{-\frac{\Delta v}{c}}) \quad (3.91)$$

DLR